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Final Report

AFOSR-TR- 88-0903

CUMULATIVE DAMAGE MODELLING IN COMPOSITE LAMINATES

Ranbir S. Sandhu, Robert L. Sierakowski, and William E. Wolfe
Department of Civil Engineering

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by

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AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
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The Ohio State University Research Foundation
1314 Kinnear Road, Columbus, Ohio 43212

FOREWORD

The work reported herein was carried out under Air Force Office of Scientific Research Grant AFOSR-86-0211 to The Ohio State University. Matching funds were provided by the Department of Civil Engineering, the College of Engineering and the Office of Research and Graduate Studies of The Ohio State University. Dr. George K. Haritos was the Program Manager at the Air Force Office of Scientific Research. At The Ohio State University, the project was supervised by Drs. Ranbir S. Sandhu, Robert L. Sierakowski and William E. Wolfe, Professors of Civil Engineering. The Principal Investigators were assisted by the machine shop staff of the Department of Civil Engineering.

ABSTRACT

Acquisition of laboratory equipment to enhance the capability of The Ohio State University for testing specimens and interrogating cumulative damage in advanced composite materials is described. The Air Force Equipment Grant AFOSR-86-0211 complemented the support provided by The Ohio State University Office of Research and Graduate Studies and the College of Engineering. The report lists the equipment purchased under the AFOSR Grant as well as delineates the overall capability for advanced materials research made possible through the combined support of The Ohio State University and the Air Force.

TABLE OF CONTENTS

LIST OF PHOTOGRAPHS

I. INTRODUCTION

Use of advanced composite materials in high-performance aerospace vehicles and components has recently experienced a dramatic increase. At The Ohio State University this development has been recognized and efforts initiated to provide the Air Force and other agencies with results of research on the behavior of such materials so that they can be more effectively used in design. The University already possessed adequate capability in analytical methods and in 1985 was awarded a grant (NO. F33615-85-C-3213) by the Air Force Wright Aeronautical Laboratories for "Modelling Cumulative Damage Processes in Composite Laminates". This project focused on the development of procedures for prediction and assessment of damage in composite laminates. The project also included identification of appropriate stress-strain laws and failure criteria for composites subjected to complex loadings. The experimental program proposed in the project required monitoring specimen delamination.

The Principal Investigators and others in the faculty of the Civil Engineering Department were also interested in enhancing their ability for research in study of deterioration of mechanical properties of composite laminates caused by damage growth in the form of matrix cracking, fiber fracture and delamination. It was considered important that materials for aerospace vehicles and components be tested in an environment closely approximating the actual conditions in space including high vacuum and extremely low temperatures. It was necessary to acquire equipment which would permit continuous monitoring of crack growth and interaction along with the structural response locally as well as globally by recording stress-strain and or stress-displacement behavior at key locations. Ultrasonic scanning and X-ray radiographic equipment were required for this purpose as well as for monitoring of damage growth. The two nondestructive evaluation methods were to complement each other. A multi-channel digital oscilloscope was required to enhance the capability to continuously monitor the mechanical behavior at key locations on a composite specimen during entire loading history. A dynamic signal analyzer was required to facilitate sequential monitoring of changes in stiffness, damping, and mode shapes to validate frequency domain calculations of structural response of composite laminates subjected to different degrees of damage.

In addition to the monitoring equipment, it was necessary to acquire a facility for preparation of specimens and to acquire or build equipment for testing the materials under a range of strain rates in order to evaluate their response to dynamic and impact loads. For application of complex loading histories and loading combinations it was necessary to install an arrangement for axial-torsion load applications over a range of loads appropriate to the experimental programs envisaged.

Pursuing a consistent policy of updating and enhancing the laboratory research facilities, the Civil Engineering Department, with support from the College of Engineering and the Office of Research and Graduate Studies of the University had acquired some equipment during the two years immediately preceding the request to the Air Force. These facilities, in place at the time the Air Force Equipment Grant was approved, included the following:

1. A microprocessor-controlled autoclave suitable for research into the behavior of both thermoset and thermoplastic composites. The autoclave has a useable work space of 13"x13"x36" and can be programmed to obtain a desired thermo-pressure cycle for fabrication with a maximum pressure of 250 psig and temperatures up to 700 degrees Fahrenheit. This equipment was acquired in 1985.

2. An MTS tension-compression torsion servo-hydraulic test machine with a capacity of 55 kips in tension-compression and 20 inch kips in torsion. This machine was acquired in 1985.

3. Three independent computer-controlled data acquisition systems. The first system, acquired through an NSF grant, is built around a Digital Equipment Corporation PDP 11/23 computer and has been in operation in the laboratory for about seven years. The other two systems, acquired through University support and through another research grant from the AFOSR (Grant 83-0055) in 1984 are controlled by microcomputers. These data acquisition systems have been configured for high-speed data collection and one of these has been previously used for monitoring liquefaction studies on saturated soils under dynamic loading. The other has been used for recording of strain gage and load cell data. Each system is capable of supplying an input signal of any desired shape and duration to the MTS controller and, therefore, to the test specimen. Monitoring and recording the response of the specimen, processing of the experimental data and subsequent analysis are all performed with the control computers.

4. A gas gun impact testing facility. This facility had been built to conduct foreign object damage type impact studies on various composite systems. Cylindrical or spherical projectiles can be used to inflict different types and degrees of damage on composite plates. The maximum speed of the projectile can be as high as 2000 ft/sec. The velocity and energy of the projectile can be adjusted by changing the applied gas pressure and weight of the projectile. This facility was built in 1985.

5. Adequate instrumentation had been acquired to simultaneously monitor the output of up to twenty electronic transducers.

The purpose of the grant was to enhance the capabilities of the Department of Civil Engineering at The Ohio State University, for testing specimens and interrogating damage in advanced composite materials. The equipment acquired was expected to complement the University's own program of development of effective laboratory facilities in the area of advanced composite materials.

II. EQUIPMENT ACQUIRED UNDER THE GRANT

In the original proposal to the AFOSR, support for the purchase of the following items of equipment was requested.

1. Nicolet Digital Oscilloscope.

Model 4094-A2, four-channel with dual floppy disc recorders.

2. X-ray Inspection System.

A constant-potential X-ray source for low absorbing materials (graphite, Kevlar, glass composites etc.)

A Phillips 100 KV X-ray interrogation system model MG104 with microprocessor.

3. Ultrasonic Scanning System.

An Ultrasonic Scanning System. for the interrogation of damaged and opaque structural composites. The unit was to consist of a work-support table, two transverse independent carriages, adjustable squirter assemblies, a computer controlled positioning system and a C-scan recorder. The squirters were to be adjustable at angles from the verticle to plus or minus 45 degrees in both the x-z and the y-z planes.

4. Integrated Dynamic Test System.

Instron Model 1331 25,000 pound 4-column load frame, hydraulic crosshead lifts and lock, 22,000 pound fatigue rated load cell, 5 gpm hydraulic power supply and servovalve, 22,000 pound actuator, and necessary electronics.

5. Dual-Channel Dynamic Signal Analyzer.

Hewlett Packard model 3562A dual channel analyzer with one dual, double sided micro-disc drive and HP-IB cable.

6. Environmental Test Chamber.

MTS model 651.12 temperature-controlled testing chamber, chamber cart Model 651.20 and water-cooled pull rods. The system was expected to be capable of a maximum temperature of 600 degrees F and a minimum temperature of -200 degrees F.

7. Axial-Torsion Hydraulic Grips.

MTS Model 646.25AT grips with an axial capacity of 55,000 pounds and 20,000 inch-pounds torsion.

The AFOSR Grant AFOSR-86-0211 as initially approved made available, funds sufficient, with The Ohio State University's cost-sharing, to purchase the first three items in the list. Later, the amount of the grant was increased and permission granted for the purchase of items #5 and #7. A change in specification of item #3 reduced its cost substantially. A reallocation of funds with permission to acquire a cryogenic vacuum environmental test chamber was approved by the AFOSR. These funds, further augmented by a generous increase in cost-sharing funds from The Ohio State University, made possible the acquisition of an additional environmental test chamber capable of simulating extremely low temperatures and very high vacuum.

All the items approved in the Grant have been acquired and installed except the Cryogenic Vacuum Chamber which was ordered near the end of the project, is currently being fabricated and is expected to be delivered shortly. The Oscilloscope and the Dynamic Signal Analyzer are installed and operational. The X-ray System and the Ultrasonic Scanning Systems are installed and operational. The Axial-Torsion Grips have been delivered and the MTS Corporation is correcting some errors in design of the connectors to attach the grips to the machine.

The detailed specifications for various items were changed slightly to obtain the latest technology at the most advantageous price. In some cases this meant that the supplier was not the same as the one who had quoted the price used in preparing the budget for the original grant. These changes were accomplished at no additional cost to the sponsor.

Brief specifications for each item of equipment actually acquired are listed in Appendix A along with photographs where relevant.

III. RELATED EQUIPMENT ACQUISITION

Items equivalent to #4 and 6 in the original list submitted to the Air Force were acquired with support provided by The Ohio State University Office of Research and Graduate Studies under a separate project. In addition, the department was able to acquire a drop hammer impact testing machine. Brief specifications and capabilities of these items are given below.

1. A Dynatup drop-hammer impact testing machine.

This machine, General Research Corporation Model 8250, is microcomputer-controlled and designed to conduct free fall impact tests on manufactured specimens, components, sheet specimens, and extruded structural shapes. The impact velocity of this model ranges from 2 ft/sec to 12 ft/sec. The applied energy can be varied from 0.47 ft-lb to 326 ft- lb by changing the drop height and the weight of the tup. The maximum drop height is 4 feet and the maximum weight is 105 pounds. A computerized data-acquisition system is used to collect the test data.

2. A Split-Hopkinson Pressure Bar.

This device was built in the machine shop of the Civil Engineering Department. The Split-Hopkinson Pressure Bar is designed to test a wide variety of monolithic and composite materials at high strain rates. The basic design is for compressive loads but the system can be easily modified for testing under tensile loads. Testing under elevated temperatures can be carried out using the environmental chamber (item #4 below). In this device, a loading pulse is provided by a striker bar (34.5 inches long) which has been accelerated by a gas gun (item # 5 below) launching mechanism. The striker bar impacts an incident bar. A stress wave is generated which is imparted to the sample which has been sandwiched between the incident bar and a third bar, the transmitter bar. The resultant strain pulse propagating through the bar is monitored by strain gages mounted on both the incident and the transmitter pressure bars. The lengths of the incident and the transmitter bars are, respectively, 14 feet and 7 feet. Both bars are 3/4 inches diameter and are made of Inconel 718 (AMS 5662).

3. Two Load Frames.

Two 30,000 pound electro-mechanical load frames, manufactured by United Testing Services, have been purchased to conduct uniaxial tension and compression tests.

4. An Environmental Chamber.

The chamber was supplied by United Test Systems to mount on either of the load frame described in item #3 above. Internal dimensions of the chamber are 20 inches in length and height, and 16 inches in width. The environmental chamber is capable of a maximum temperature of 1000 degrees F and a minimum temperature of -100 degrees F.

Appendix B lists brief specifications for these items as well as other equipment acquired/built for the laboratory and contains some photographs.

IV. RESEARCH CAPABILITY ATTAINED

The immediate use of the equipment purchased through this grant, envisaged at the time of the award, was in the experimental component of the Air Force Grant NO. F33615-85-C-3213 awarded to The Ohio State University in 1985 by the Air Force Wright Aeronautical Laboratories for "Modelling Cumulative Damage Processes in Composite Laminates". This project focused on the development of procedures for prediction and assessment of damage in composite laminates. The project also included identification of appropriate stress-strain laws and failure criteria for composites subjected to complex loadings. The experimental program included in the project required monitoring specimen delamination. However, even though not yet complete, the laboratory facilities described in the previous sections are currently being used in a variety of other research programs and several more applications are envisioned.

A determination of the level of damage experienced by graphite/epoxy composites subjected to low velocity impact damage is an important Air Force goal. At present, design standards require that composite sections be able to withstand impact energies of up to 100 ft.-lbs. An exprimental program to determine the actual damage to composite plates subjected to different levels of impact energy has recently begun. The equipment utilized in this study is the drop tester (item #1 in Section III), the Ultrasonic Scanning System and the X-Ray system obtained under this grant.

In two programs, one recently started and one continuing, we are studying the effects on composite systems of impacts of velocities higher than those attainable with a drop tester. In the continuing project impacts typical of those to be expected of runway debris are being generated using the gas gun (item #5 in Section III). The targets are high-strength concrete plates simulating a section of a protective structure. Impact velocities are recorded using the Nicolet Digital Oscilloscope obtained through this grant. In the new project, small lightweight spheres are being propelled at supersonic speeds, by the gas gun, at composite plates. In this case the high velocity combined with the small size of the projectile make very high speed data collection such as that available on the Nicolet Digital Oscilloscope (2 MHz) necessary for accurate measurements.

In a fourth project currently underway in the laboratory we are studying the effects of various sterilization techniques on the unique stress-strain properties of some widely used dental (orthodontal) wires. In this program the high strength and deformation characteristics of several types of dental wires are determined before and after the wires are subjected to five different procedures for sterilization. The laboratory equipment used in this study includes the United McGill Autoclave described in Section III (item #6) and the United Test Systems load frame (item #3, Section III). We intend to use the MTS axial-torsional frame with these materials as soon as the grips are properly nstalled (item #7, Section III).

In addition to the projects currently underway, there are several research areas we would like to explore and for which our laboratory facilities give us unique capabilities. With the environmental chamber being built for us by CVI, we are able to reproduce the most important aspects of the near space environment (very low temperature and atmospheric pressures) in the laboratory. Because the chamber is built around a load frame, the effects of this environment on the behavior of composite structural elements can be determined. We are working with CVI to incorporate into the chamber the capability of providing a directed energy source so that localized heating of the test specimen can be accomplished. With this capability we can subject samples to the extremes of heat and cold that space structures can be expected to experience.

Optimization of space structures is a very important part of the Department's analytical research program. With the acquisition of the laboratory facilities provided for in the program, experimental verification of the analytical work can be accomplished. System identification by the measurement of natural frequencies, mode shapes and damping is possible using the Zonic Spectrum Analyzer purchased through this grant. Real time analysis of these most important system parameters can now be readily performed at four locations (with the potential of 16 more). Changes in response caused by changes in the system, e.g., reducing the weight or stiffness of a member, inducing some damage, repositioning some feedback controls, can be immediately measured and the consequences evaluated.

Using the MTS axial-torsional loading frame to apply load to a specimen allows the investigator to study the development of damage under complex stress paths. Attaching an ultrasonic C-scan device to the load frame the investigator is able to interrogate the specimen without changing the stress field by removing it from the load frame. Since the specimen does not have to be removed to make a damage estimate, many more C-scan records can be made to obtain an almost continuous record of growth of damage.

IV. SUMMARY

The Civil Engineering Department of The Ohio State University, with the help provided by the Air Force Office of Scientific Research, The Ohio State University Office of Research and Graduate Studies, and the College of Engineering has been able to set up an effective laboratory for the testing and evaluation of advanced composite materials subjected to a variety of loads applied over a wide range of rates of loading and environmental conditions. The conditions are similar to those the materials would encounter in use for aerospace vehicle components or other inspace uses.

This equipment includes an autoclave for preparation of specimens; microprocessor controlled (for reproducibility of test data) testing machines with range of loading rates from slow to very high including impact; environmental simulation equipment including a variable temperature chamber with maximum temperature of 1000 degrees F and a cryogenic vacuum chamber with pressures as low as 10^{-7} torr and temperatures as low as -250 degrees F; and interrogation apparatus, including X-ray and ultrasonic scanning during testing, rapid data collection equipment including a high speed oscilloscope and a multi-channel dynamic signal analyzer, and facilities for the collection, reduction and analysis of data.

The newly acquired facilities will be extremely useful for conduct of research under the Air Force Wright Aeronautical Laboratories (Grant NO. F33615-85-C-3213) on "Modelling Cumulative Damage Processes in Composite Laminates". This project focuses on the development of procedures for the prediction and assessment of damage in composite laminates. The project also includes identification of appropriate stress-strain laws and failure criteria for composites subjected to complex loadings. The experimental program proposed in the project requires monitoring delamination.

The Civil Engineering Department has also enhanced its ability for research in the study of deterioration of mechanical properties of composite laminates caused by damage growth in the form of matrix cracking, fiber fracture and delamination. Materials for aerospace vehicles and components can now be tested in an environment closely approximating the actual conditions in space including high vacuum and extremely low temperatures. The equipment acquired permits continuous monitoring of crack growth and interaction along with the structural response locally as well as globally by recording stress-strain and or stress-displacement behavior at key locations. Ultrasonic scanning and x-ray radiographic equipment are now available for this purpose as well as for monitoring of damage growth. The two nondestructive evaluation methodologies are to complement each other. A multi-channel digital oscilloscope has enhanced the capability to continuously monitor the mechanical behavior at key locations on a composite specimen during entire loading history. The dynamic signal analyzer will facilitate sequential monitoring of changes in stiffness, damping, and the mode shapes for the frequency domain of structural response of composite laminates subjected to different degrees of damage.

Equipment for preparation of specimens and for testing the materials under a wide range of rates of strain to evaluate their response to dynamic and impact loads has been acquired. For application of complex loading histories and loading combinations, an axial-torsional load frame capable of applying loads over a range of rates and magnitudes has been installed.

Future enhancements to the laboratory facilities could include non-contacting multiaxial displacemt systems, high speed cameras for recording dynamic events and instrumentation for control and interrogation of behavior of specimens enclosed in environmental chambers and/or subjected to extreme environmental conditions.

APPENDIX A

EQUIPMENT ACQUIRED UNDER GRANT AFOSR-86-0211

1. Nicolet Digital Oscilloscope.

The equipment purchased from Nicolet Instrument Corporation, 5225 Verona Road, Madison, Wisconsin 53711, departed slightly from the specification stated in the original proposal. The oscilloscope purchased is:

Model 4094-B2, mainframe (16K words x 16 Bits) with pen output and 1B-44 Digital I/O part #886-4094B2. It also has the following features.

Two-channel plug-in with 16K buffer memory, 12-Bit resolution, 2MHZ sampling rate cursor trigger and averaging.

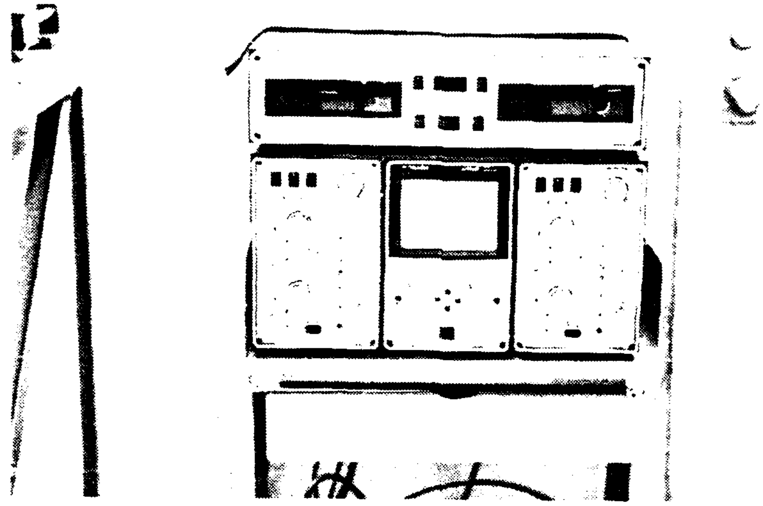
A self-contained CRT to display waveforms, cursors and numerics along with electronically generated grid.

Oscilloscope cart.

The oscilloscope is capable of saving and retrieving records with the two 5 1/4 inch floppy disk drives and can be interfaced with the personal computer-based data acquisition systems through the RS232 port. Software includes a mathematical package and the advanced data acquisition package.

Photograph on the following page shows the Nicolet oscilloscope on its cart.

PHOTOGRAPH NO. 1.   THE NICOLET DIGITAL OSCILLOSCOPE



2. The X-ray Inspection System.

This unit acquired from Test Equipment Dist., 1370 Piedmont, Troy, Michigan 48084 includes the following components:

MCN 101 100KV, 15 MA unit, #9421-172-59042

Microprocessor Control (unit MGC 20) with housing (unit 3U), #9421-170-39502, and #9421-166-87012

100 KV Minus H.T. generator, #9421-170-28202

Water-flow safety valve with 10m cable, #9421-167-34112

10 KV H.T. cable 5m, cooling water hose 20m, #9421-166-29003 and #9421-173-16052

X Rite Model 301 Densitometer

High Intensity Model 65D1 viewer w/spot capabilities

Victoreen Model 492 Survey meter

Developer, Fixer and Dryer

Film cassettes 14"x17", 10"x12", head letters, hangers inserts, screens etc. to complete the unit for operation.

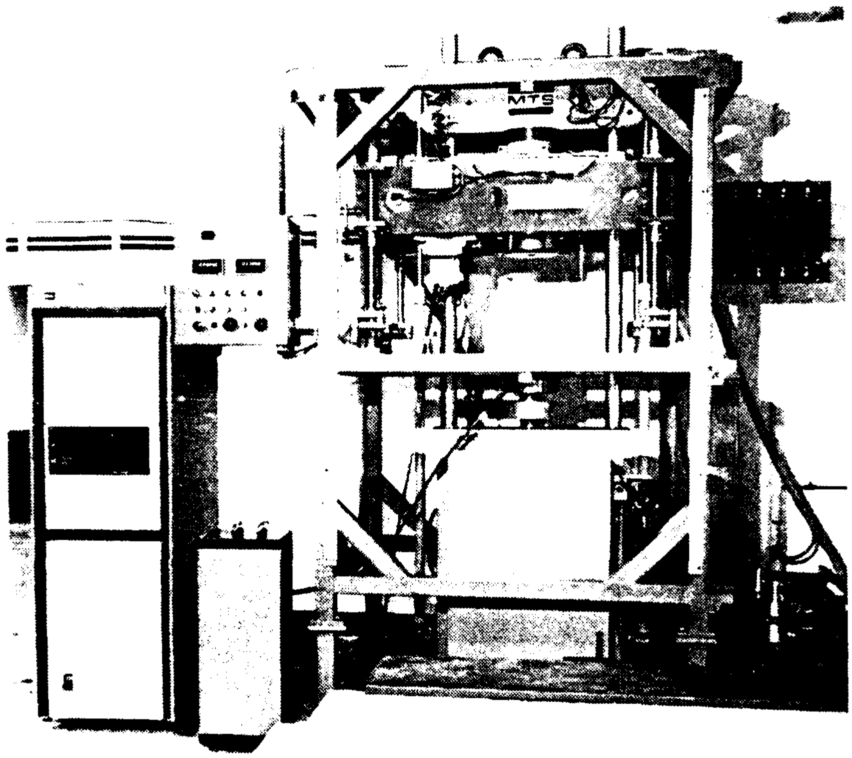
3. The Ultrasonic Scanning System.

This system for the interrogation of damaged and opaque structural composites consists of a work-support table, two transverse independent carriages, adjustable squirter assemblies, a computer-controlled positioning system and a C-scan recorder.

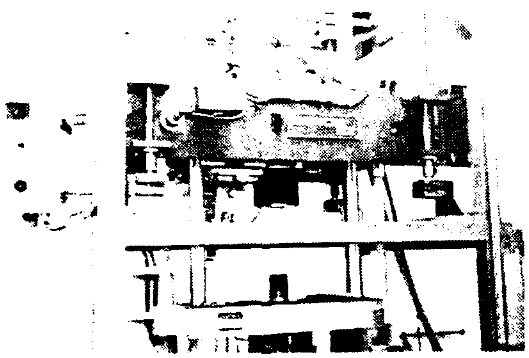
The test system has been build around the MTS test machine. The finished frame assembly can be installed on the MTS test machine and is removable for use in a reservoir tank assembly. The transducer carriage assembly consists of two mounted transducers. The two assemblies are linked to ensure that each carriage will ride in direct opposition during scanning. Each transducer assembly is served with a manipulator assembly allowing for movement in the vertical and horizontal planes as well as in and out movement between the transducers. the range of motion is 25 inches vertically, 22 inches horizontally and 5 inches in and out between transducers. The manipulator assemblies have a locking assembly to properly secure the transducer/-squirter assemblies. Two squirter assemblies and a recirculation system consisting of a pump, filter, and reservoir are integral parts of the system. The operation of the system in manual as well as automatic run modes is controlled from an operator console. The system is connected to an IBM PC based data reduction system. The entire assembly is mounted on leg pads to interface with the MTS test machine.

Photographs No. 2 and 3 show the ultrasonic scanning system mounted on the MTS testing machine.

PHOTOGRAPH NO. 2. THE ULTRASONIC SCANNING SYSTEM (MOUNTED ON THE MTS TESTING MACHINE)



PHOTOGRAPH NO. 3. THE ULTRASONIC SCANNING SYSTEM (A CLOSE-UP VIEW)

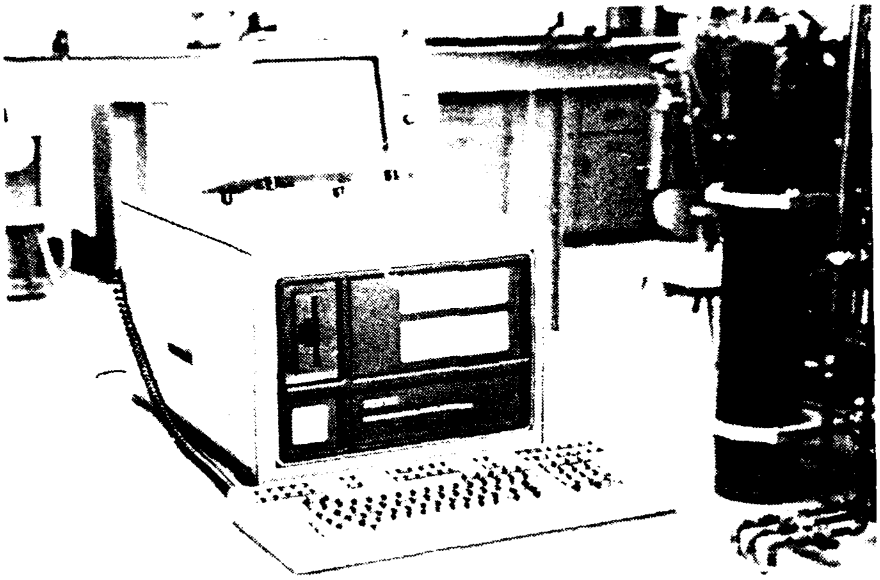


4. The Four-Channel Dynamic Signal Analyzer.

The specifications for the Spectrum Analyzer were changed at the time of ordering equipment. It had become possible to acquire a four-channel analyzer with option for future expansion up to 20 channels at a price only slightly (less than 18%) higher than the original quotation for the two-channel analyzer. Thus instead of the Hewlett Packard model 3562A dual channel analyzer, a Zonic Model 6088-4-M multichannel signal processor has been acquired from Zonic Corporation 2000 Ford Circle, Milford, Ohio 45150. The system includes 618 Kilobyte 3.5" floppy disk, 15MB HD, automatic input gain selection with signal overload detection and rejection, 9" monochrome monitor along with Zonic modal analysis software with SDOF and MDOF curve fitters, FRF sysnthesis, dual input random excitation; and Zonic calculator analysis software featuring block arithmetic, flexible plot formats, HP/GL pen plotter support, data file format conversion to ASCII. The data acquisition system allows data to be sampled at rates up to 102,400 samples per second for each input channel

Photograph No. 4 shows the four-channel signal analyzer.

PHOTOGRAPH NO. 4.   THE FOUR-CHANNEL SIGNAL ANALYZER



5. The Axial-Torsion Hydraulic Grips.

MTS Hydraulic Collet Grips were purchased from the MTS Systems Corporation, 1010 Woodman Drive, Suite 140, Dayton, Ohio 45432. These are Model 646-25AT-003 along with mounting adapters to MTS Model 809 Axial-Torsion system with an axial capacity of 55,000 pounds and 20,000 inch-pounds torsion. The grips will allow testing under combined axial-torsional loading and under low cycle fatigue. They can accomodate round, flat or threaded specimens in a wide variety of materials and thicknesses.

Photograph No. 5 shows the grips on a table before being installed on the MTS machine.

PHOTOGRAPH NO. 5.   THE MTS HYDRAULIC COLLET GRIPS

6. Cryogenic Environmental Chamber.

This item supplied by the CVI Corporation, Columbus, Ohio will be a high vacuum tensile test chamber with a liquid nitrogen shroud. The chamber will operate at a high vacuum level of $10E^{-7}$ torr or higher with or without the shroud installed. It will be constructed of 300 series stainless steel with an acrylic window and viton "O" ring seals. The shroud is constructed of 1100 series aluminum with the interior surface of the shroud painted with 3M ECP 2200 paint. It will have a 24 inch diameter window in the door for viewing the test specimen. The chamber is provided with openings for the tensile test. An eight-pin instrument feedthrough will be provided for instrumentation attachments to the test sample. A cryopump penetration and KF-25 penetration are provided for vacuum pumping. Two penetrations (one inch approx.) will be located in the top plate for LN2 supply and vent to the shroud. A mechanical roughing pump, a CVI TM150 cryopump and necessary valves, interconnecting piping and high vacuum instrumentation are provided with the chamber.

APPENDIX B

RELATED EQUIPMENT ACQUISITION

1. The Drop-hammer Impact Tester

This machine, General Research Corporation Model 8250 , is designed to perform impact tests on manufactured specimens, components, sheet specimens, and extruded structural shapes. The impact velocity of this model ranges from 2 ft/sec to 12 ft/sec under gravity driven mode. The applied energy ranges from 0.47 ft-lb to 326 ft-lb which can be adjusted by changing the height and the weight of the tup. The maximum drop height is 4 feet and the maximum weight is 105 pounds. The system is fully microprocessor-controlled. A computerized data-acquisition system GRC MOdel 730-I is used to collect the dynamic test data. The system includes a high speed data acquisition board, a velocity detector, an IBM PC/XT computer, a Hewlett-Packard 2-pen plotter and an Epson FX-80 printer.

Photograph No. 6 shows the Dynatup impact tester along with the microprocessor control.

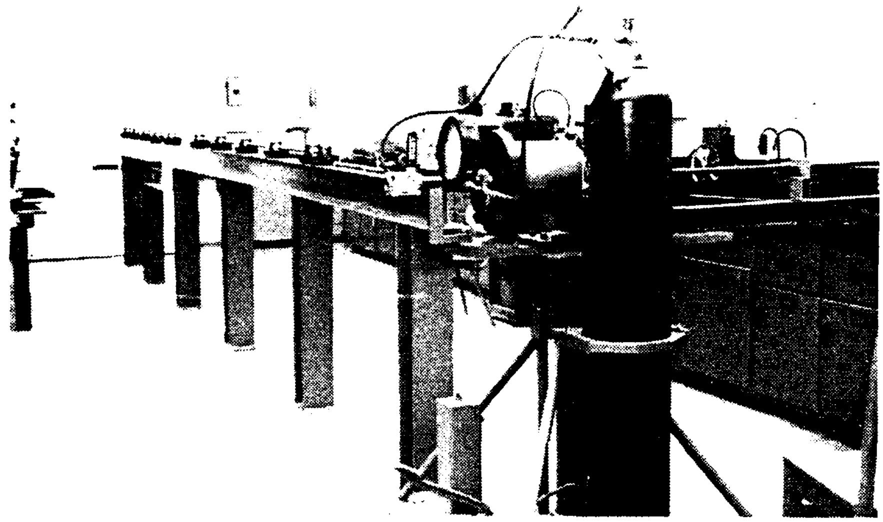
PHOTOGRAPH NO 6. THE DYNATUP IMPACT TESTER

2. The Split-Hopkinson Pressure Bar

The Split-Hopkinson Pressure Bar is designed for compressive loads but the system can be easily modified for testing under tensile loads. Testing under elevated temperatures can be carried out using the environmental chamber (item #4 below). The loading pulse is provided by a striker bar (34.5 inches long) which is been accelerated by a gas gun (item # 5 below) launching mechanism. The striker bar impacts an incident bar. A stress wave is generated which is imparted to the sample which is sandwiched between the incident bar and the transmitter bar. The resultant strain pulse propagating through the bar is monitored by strain gages mounted on both the incident and the transmitter pressure bars. The lengths of the incident and the transmitter bars are, respectively, 14 feet and 7 feet. Both bars are 3/4 inches diameter and are made of Inconel 718 (AMS 5662).

Photograph No. 7 shows a view of the Split-Hopkinson bar supported on a system of bearings attached to a girder aligned so that the center of the bar is at the same level as the barrel of the gas gun.

PHOTOGRAPH NO. 7.   THE SPLIT-HOPKINSON PRESSURE BAR

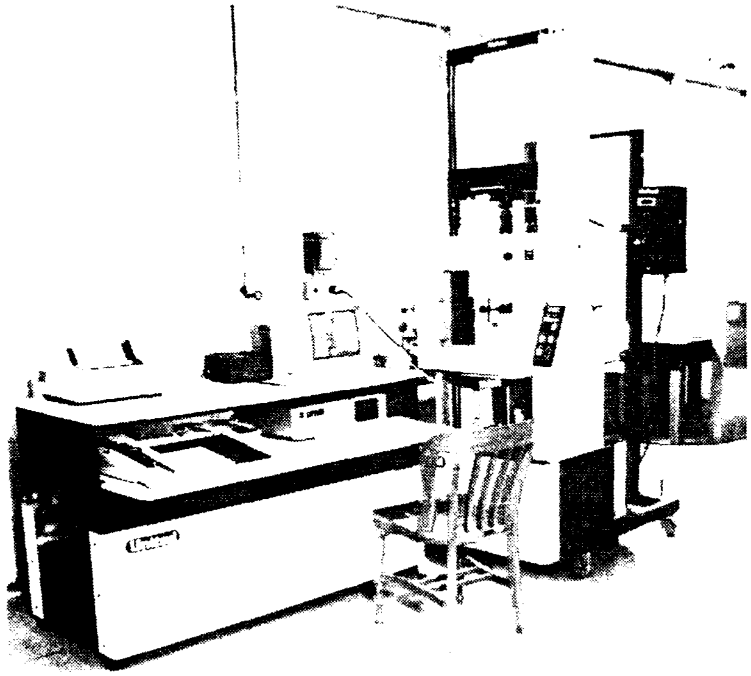


3. The Environmental Test Chamber.

This chamber was supplied by United Test Systems. It mounts on the load frame (item #4 below). Internal dimensions of the chamber are 20 inches in length and height, and 16 inches in width. The environmental chamber is capable of a maximum temperature of 1000 degrees F and a minimum temperature of -100 degrees F. Heating elements are 1800 watt 7.5 Amp x 4; cooling is by carbon dioxide or liquid nitrogen; temperture uniformity is within 5 degrees F after stabilization; and control performance is 2 degrees F after stabilization.

Photograph No. 8 shows the environmental chamber mounted on the 30,000 pound load frame along with the microprocessor console controlling the test and recording/displaying test data.

PHOTOGRAPH NO. 8. THE ENVIRONMENTAL TEST CHAMBER
(MOUNTED ON THE LOAD FRAME)

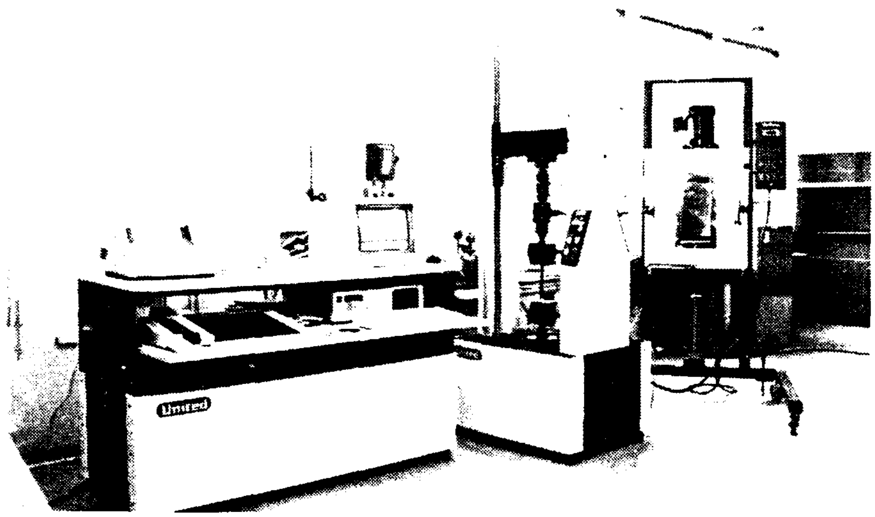


4. The Load Frames

Two 30,000 pound electro-mechanical load frames, manufactured by United Testing Services, have been purchased to conduct uniaxial tension and compression tests. The tension grips can handle specimens up to 2 inch width, the compression plattens are six inch diameter and the distance between plaattens can be as large as three feet. Both testing systems are microprocessor-controlled and equipped with dedicated data acquisition systems controlled by personal computers. The software will test specimens in accordance with ASTM E8 automatically. The manual program allows for test speeds up to 2 inches per minute. Cyclic loading is included.

Photograph No. 9 shows the 30,000 pound load frame. The environmental chamber mounted on a frame, which can be rolled into position for attachment to the load frame, is in the background.

PHOTOGRAPH NO. 9. THE 30,000 POUND LOAD FRAME (WITH MICROPROCESSOR CONTROL)

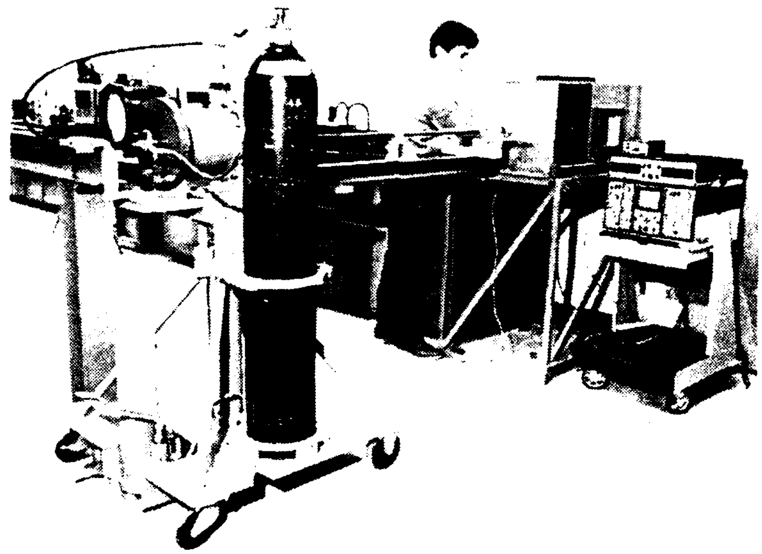


5. The Gas Gun Impact Test Facility

Sudden release of compressed gas propels a projectile along a barrel to a target mounted in an enclosed chamber equipped with viewing ports. The projectile material and shape can be selected appropriately. The velocity and energy of the projectile can be adjusted by changing the applied gas pressure and weight of the projectile. The chamber size is approximately 380 cubic inches. Two gun barrel lengths are available viz.,5 feet and 14 feet. The velocity is measured using LED light-sensor velocity gages. Pressure transducers are used to monitor chamber pressures. The maximum speed of the projectile can be as high as 2000 ft/sec.

Photograph No. 10 shows a view of the gas gun which is mounted on a frame on rollers. The box which houses the target is shown in the figure. Note the window for inspection and interrogation.

PHOTOGRAPH NO. 10. THE GAS GUN

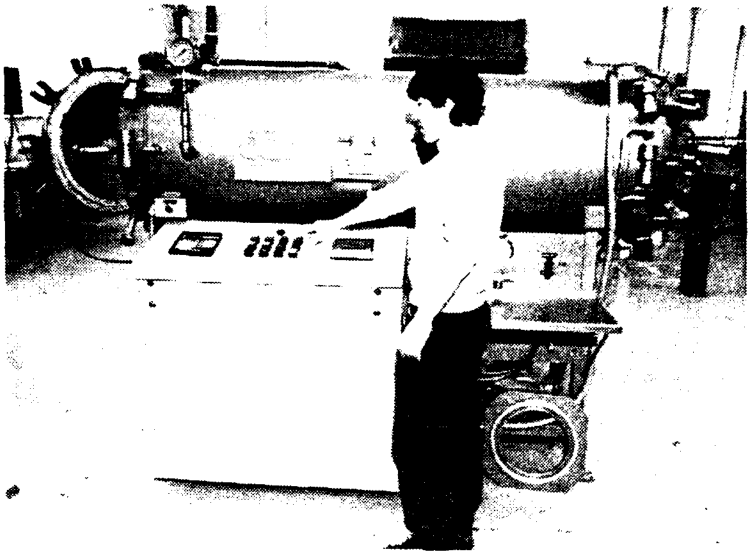


6. The Autoclave

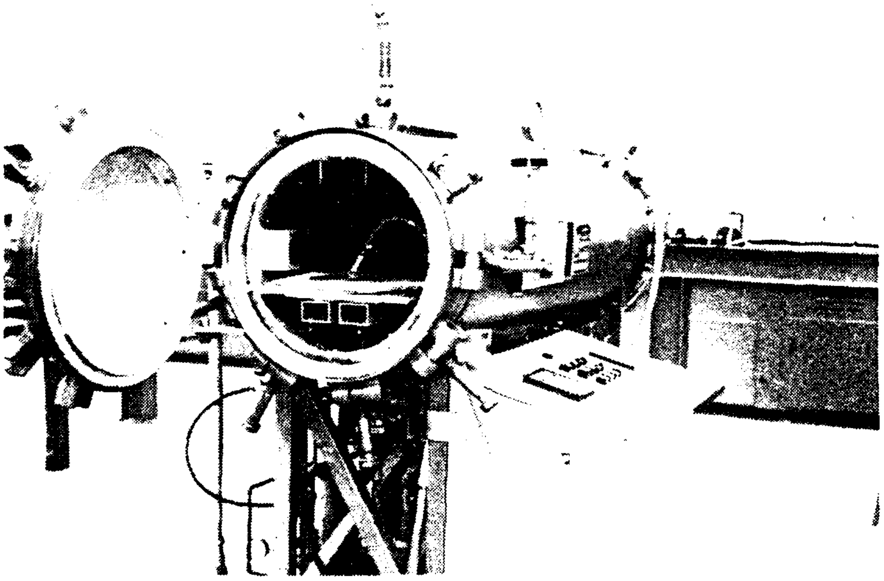
The autoclave was manufactured by United McGill of Columbus, Ohio. It is fully microprocessor-controlled and can be programmed to obtain a desired thermo-pressure cycle for fabrication with a maximum pressure of 250 psig and maximum temperatures up to 700 degrees Fahrenheit. It has a shell 22.6 inches in internal diameter providing a workspace 13 inches square by 36 inches long. The pressurizing medium is nitrogen. The centrifugal fan and motor assembly provide an air circulation velocity within the autoclave of not less than 300 feet per minute. The electric heaters are incology sheathed tubular elements, rack mounted. Heater is rated at 9.6 KW, 230 V, single phase. Heat exchanger cooling coil is designed to remove heat at an average rate of 16,000 BTU per hour from 700 degrees F to 150 degrees F by cooling a constant volume of 350 gpm of nitrogen at 225 psig with approximately 3gpm of 70 degrees F water. The vacuum supply pump is piston type, direct driven, oilless, twin cylinder. It has a 5.0 cfm free air capability at 0 inches of mercury. It is rated for a vacuum of 27.5 inches of mercury on closed suction test.

Photographs No. 11 and 12 show the autoclave along with its controls.

PHOTOGRAPH NO. 11. THE MICROPROCESSOR-CONTROLLED AUTOCLAVE



PHOTOGRAPH NO. 12. LOADING END (OPEN) OF THE AUTOCLAVE



7. The MTS Tension-Compression/Torsion Machine

The MTS tension-compression torsion servo-hydraulic test machine has a capacity of 55 kips in tension-compression and 20 inch kips in torsion. It is controlled by a 456.20 MTS microconsole. The operation can be either load or displacement-controlled. Specimens can be tested up to 20 Hz. The machine admits specimens up to three feet in length.

8. Data Acquisition Systems

Three independent computer-controlled data acquisition systems are available.

The first system is built around a Digital Equipment Corporation PDP 11/23 computer and is equipped with a Hewlett Packard plotter. This system has been previously used for monitoring liquefaction studies on saturated soils under dynamic loading.

The other two systems are controlled by microcomputers. These have been used for recording of strain gage and load cell data. Data handling is organized around the ASSYST software. The computers can receive data at rates up to 20,000 words/second. A backup tape facility is used for storage and archival of test data. Dedicated plotting and printing facilities are available.

All the three systems have been configured for high-speed data collection. Each is capable of supplying an input signal of any desired shape and duration to the MTS controller and, therefore, to the test specimen. Monitoring and recording the response of the specimen, processing of the experimental data and subsequent analysis are all performed with the control computers.